On the Nature of the Purported Common Proper Motion Companions to the Exoplanet Host Star 51 Peg

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Greaves (2006) proposed that three red, high proper motion stars within 10° of 51 Peg (NLTT 54007, 54064, & 55547) are co-moving companions to this famous exoplanet host star. While the stars clearly have proper motions similar to 51 Peg, the inferred kinematic parallaxes for these stars produce extremely inconsistent color-magnitude positions 2 to 4 magnitudes below the main sequence. All three stars are likely to be background stars unrelated to 51 Peg.

1 Introduction

In October 1995, Mayor & Queloz (1995) reported the discovery of a Jovian-mass companion orbiting the solar-type star 51 Peg in a 4.2 day orbit. The companion 51 Peg b is the prototype of the 'hot Jupiter' class, and the 51 Peg system has been the source of intense study over the past decade and a half. Thus far, surveys have failed to identify any reliable stellar companions, either within a few arcseconds (Luhman & Jayawardhana 2002), and out to ∼5' (Raghavan et al. 2006). The existence of low-mass stellar companions to exoplanet host stars are of dynamical interest in the quest to understand the diversity of planetary systems (e.g. Desidera & Barbieri 2007).

Greaves (2006) reported that three faint stars might be co-moving with 51 Peg: NLTT 55547 (1°.1 away from 51 Peg), NLTT 54064 (7°.1) and NLTT 54007 (8°.4). It is extremely unlikely a priori that any of these stars would be *bound* companions to 51 Peg as the maximum observed separation for ∼1 $M_\odot$ stars is in the range ∼2500-10000 AU (∼0.012-0.048 pc; Abt 1988, Close et al. 2003), and the projected separation of the nearest of these (NLTT 55547) is 0.28 pc (∼58000 AU) if codistant with 51 Peg. The association of these stars with 51 Peg predicates not only on the proper motions of these stars, but also their color- magnitude data (and of course parallax and radial velocity). In this contribution I conclude that for all three stars the color-magnitude data combined with the kinematic distances (predicted by combining their proper motions and the space velocity of 51 Peg) are sufficient to rule out companionship to 51 Peg.

2 Analysis

2.1 51 Peg

Astrometric data for 51 Peg are presented in Table 1, with the position, proper motion and parallax coming from van Leeuwen (2007). Longer baseline proper motions by Hog et al. (2000) and Roeser et al. (2008) agree within 2σ along each component. The systemic radial velocity for 51 Peg comes from Nidever et al. (2002), and no long-term radial velocity trend for 51 Peg was reported. Since the Sun and 51 Peg are of nearly identical spectral type, and the zero point of the radial velocity is calibrated using the Sun (via measurements of radial velocities of minor planets), the systemic radial velocity of 51 Peg should accurately correlate to the true radial velocity within $\sim$0.1 km s^{-1} (which is the uncertainty I adopt; see discussion by Nidever et al. 2002). Hence, the galactic velocity estimated and quoted in Table 1 should accurately represent the center-of-mass velocity of the 51 Peg system to within $\pm$0.1 km s^{-1} with respect to the solar system's barycenter. The velocity vector in Table 1 is on the Galactic Cartesian system where U is directed towards the Galactic center, V is in the direction of Galactic rotation, and W is towards the North Galactic pole. This velocity vector is used to calculate the vertex of 51 Peg - i.e. the point on the celestial sphere where the proper motion vector of any star with identical velocity will point (essentially the "convergent point" for a single star rather than an entire cluster; e.g. Atanasijevic 1971). The vertex position in Table 1 is accurate to $\pm$0°.13.

51 Peg is an old Population I G-dwarf with an isochronal age of 6.8 $\pm$ 1.5 Gyr (Takeda et al. 2007) and chromospheric activity age similarly in the range of 6.1-8.1 Gyr (Mamajek & Hillenbrand 2008). 51 Peg is also metal-rich ([Fe/H] = 0.20; Valenti & Fischer 2005), so not only would any physical companion have a velocity similar to that of 51 Peg, but

Table 1 Properties of 51 Peg

Property	Value	Ref.
α(ICRS, J1991.25)	$344^\circ.36604474$	1
δ(ICRS, J1991.25)	$+20^\circ.76868422$	1
Parallax	64.07 ± 0.38 mas	1
Distance	15.61 ± 0.09 pc	2
μ_α	207.25 ± 0.31 mas yr^{-1}	1
μ_δ	60.34 ± 0.30 mas yr^{-1}	1
Radial Velocity	–33.225 km s^{-1}	3
Velocity (U)	-15.40 ± 0.09 km s^{-1}	2
Velocity (V)	-29.66 ± 0.07 km s^{-1}	2
Velocity (W)	$+15.56 \pm 0.08$ km s^{-1}	2
Speed (S)	36.86 ± 0.08 km s^{-1}	2
Vertex (α)	$139^\circ.21 \pm 0^\circ.13$	2
Vertex (δ)	$-11^\circ.91 \pm 0^\circ.12$	2

References: (1) van Leeuwen (2007), (2) calculated by author using other data in table, (3) Nidever et al. (2002).

it would be expected to be of the same age and metal-rich as well.

2.2 NLTT 55547

NLTT 55547 (= LP 401-32 = 2MASS J23003379+2135223) is situated $1^\circ.03$ from 51 Peg. Its position, proper motion, and relevant photometry are listed in Table 2. There is no published spectral type for the star, with Luyten (1979) simply suggesting that the star was "k-m" type based on color. There are multiple estimates of a V magnitude based on photographic plate scans: 15.93 (Lepine & Shara 2005), 15.61 (Salim et al. 2003), 15.74 ± 0.34 (Lasker et al. 2008), and I estimate 15.48 based on combining the USNO A2.0 B and R magnitudes. I adopt a median V magnitude of 15.68 based on these 4 estimates. The (V-Ks) color (4.58) is consistent with the mean color of M3V stars in the CNS3 catalog (Gliese & Jahreiss 1991) using photometry compiled by Neill Reid[1]. The (H-K_s) color is consistent with being in the range of M1V-M3.5V (1σ range), using median colors of M dwarfs compiled by the author by cross-referencing 2MASS photometry (Cutri et al. 2003) with M dwarfs classified on the Kirkpatrick-Henry system of standards in the Dwarf Archives database (Gelino, Kirkpatrick, & Burgasser 2009)[2]. I conclude that a photometric estimate of the star's spectral type is $\sim$M3V.

I estimate the proper motion for this star using the same positions used by Lepine & Shara (2005), and recover the proper motion quoted by Lepine & Shara to within 0.5 mas yr^{-1}. I adopt their proper motion value with an estimated uncertainty of 4 mas yr^{-1}. I follow the techniques used in Mamajek et al. (2002) and Mamajek (2005) to rotate the equatorial proper motion into components pointed towards the 51 Peg vertex (μ_υ) and perpendicular (μ_τ). One can also calculate a predicted cluster parallax distance (i.e. a "kinematic distance"), and combine that predicted distance with the μ_τ to estimate a peculiar velocity (i.e. an estimate of the velocity of the star perpendicular to the component of its velocity directed towards the 51 Peg vertex). I rotate the equatorial proper motion for NLTT 55547 into the proper motion components towards the 51 Peg vertex (μ_υ = 210 ± 4 mas yr^{-1}) and perpendicular (μ_τ = 5 ± 4 mas yr^{-1}). If NLTT 55547 has the same 3D velocity as 51 Peg, its proper motion toward the 51 Peg vertex (situated $153^\circ.4$ away) suggests a distance of 16.6 $\pm$ 0.3 pc (parallax ϖ = 60.2 ± 1.2 mas), and peculiar velocity v_{pec} = 0.4 $\pm$ 0.3 km s^{-1}. This solution predicts that NLTT 55547 would have a radial velocity of -33.0 $\pm$ 0.1 km s^{-1}. If the kinematic distance is correct than the true separation from 51 Peg is 1.0 pc, considerably more than the projected separation of 0.28 pc if NLTT 55547 were codistant with 51 Peg. An object at the celestial position of NLTT 55547, but with identical distance and velocity vector as 51 Peg, would have a proper motion of μ_α, μ_δ = 213.1, +65.7 mas yr^{-1} (i.e. nearly identical μ_δ, but μ_α deviant by 3.5σ). An object at the celestial position of NLTT 55547, with the velocity vector of 51 Peg, but distance of 16.6 pc, would have a proper motion of μ_α, μ_δ = 200.4, +61.8 mas yr^{-1} - i.e. within 4 mas yr^{-1} and 1σ of the observed proper motion components. So to force the projected motion of NLTT 55547 to match the predictions for a star comoving with 51 Peg, NLTT 55547 would have to be slightly further away (16.6 pc) than 51 Peg (15.6 pc).

Does NLTT 55547's photometric data seem consistent with the distance predicted by its potential co-motion with 51 Peg? At the kinematic distance of 16.6 $\pm$ 0.3 pc, NLTT 55547 would have an absolute magnitude of M_{Ks} = 10.01 $\pm$ 0.05. I determined the range of plausible absolute K_s magnitudes for M dwarfs of (V-K_s) $\simeq$ 4.57 using Figure 2 of Johnson & Apps (2009). Johnson & Apps (2009) also provide an absolute magnitude offset as a function of [Fe/H]. The predicted M_{K_s} for the main sequence for (V-K_s) = 4.57 is M_{K_s} = 6.54, and correcting for the slightly higher metallicity of 51 Peg ([Fe/H] = 0.20), one predicts an absolute magnitude of 6.10 (see Figure 1). Hence, if NLTT 55547 lies at the kinematic distance of 16.6 pc (consistent with comoving with 51 Peg), then *the predicted absolute K_s magnitude is 4 magnitudes too faint for its (V-K_s) color*. The conclusion is obviously the same if one simply adopts the distance of 51 Peg for NLTT 55547. While Greaves (2006) states that the derived "absolute magnitude value is not inappropriate for a cooler spectral class M dwarf", the colors are clearly consistent with an early ($\sim$M3) dwarf. Typical stars with $M_{K_s} \simeq 10$ have (V-K_s) colors of $\sim$8 to $\sim$10, hence no reasonable amount of photometric error could explain the offset. If NLTT 55547 is a typical mid-M dwarf, its (V-K_s) and K_s data are consistent with a distance modulus of $\sim$4.6 mag, a photometric distance of $\sim$80 pc, and inferred tangential velocity of $\sim$79 km s^{-1}.

I conclude that despite the remarkable match of proper motion between NLTT 55547 and 51 Peg, the color- mag-

[1] http://www.stsci.edu/$\sim$inr/cmd.html

[2] http://spider.ipac.caltech.edu/staff/davy/ARCHIVE/index.shtml

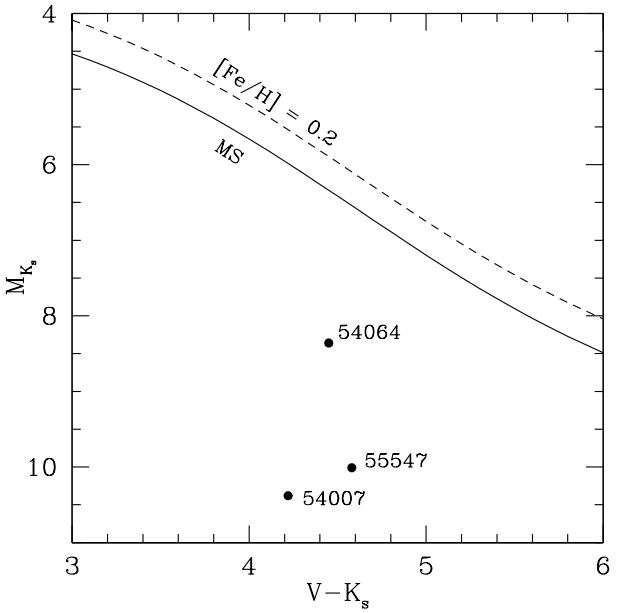

Fig. 1 V-K_s color vs. absolute magnitude M_{Ks} diagram. The main sequence of Johnson & Apps (2009) is shown as a *solid line*, which they claim corresponds to the mean metallicity of field M dwarfs ([Fe/H] = -0.05). Their sequence for [Fe/H] = +0.2 (the metallicity of 51 Peg) is shown as a *dashed line*. The color-magnitude positions of the NLTT stars at their kinematic distances (assuming they share the space velocity of 51 Peg) are plotted as *filled circles*.

nitude data are completely inconsistent with the two stars being physically related.

2.3 NLTT 54064

NLTT 54064 (= LP 460-37 = 2MASS J22311528+1709444) is situated 7°.17 from 51 Peg. Its position, proper motion, and relevant photometry is listed in Table 3. There is no published spectral type for NLTT 54064, however Luyten (1979) surmised that it was "m" class based on its colors. Several authors list V magnitudes: Rapaport et al. (2001) report 13.097 ± 0.058, Ducourant et al. (2006) report 13.262 ± 0.077, Droege et al. (2007) report 12.415 ± 0.144, and Lepine & Shara (2005) list 13.15. I adopt a median V magnitude of 13.12. The star's V-K_s and H-K_s colors are consistent with an ∼M2 dwarf. Lepine & Shara (2005) estimate a photometric distance of 32.5 ± 9.8 pc. The proper motion estimates for NLTT 54064 across several catalogs agree within their errors (Salim et al. 2003, Lepine & Shara 2005, Ducourant et al. 2006, Roeser et al. 2008). I adopt the UCAC2 proper motion as the best available (Zacharias et al. 2004).

The proper motion of NLTT 54064 directed towards the vertex of 51 Peg is μ_v = 216.0 ± 4.2 mas yr^{-1}, and the perpendicular component is μ_τ = 16.2 ± 4.2 mas yr^{-1}. The predicted kinematic distance (assuming NLTT 54064 shares the same velocity as 51 Peg) is 11.6 ± 0.2 pc (parallax ϖ = 86.5 ± 1.8 mas), and the predicted radial velocity

Table 2 Properties of NLTT 55547

Property	Value	Ref.
α(ICRS, J2000)	345°.140900	1
δ(ICRS, J2000)	+21°.589565	1
μ_α	199 ± 4 mas yr^{-1}	1
μ_δ	65 ± 4 mas yr^{-1}	1
V mag	15.68	1
J mag	11.957 ± 0.023	2
H mag	11.362 ± 0.022	2
Ks mag	11.114 ± 0.018	2
(J-H)	0.595 ± 0.032	2
(H-Ks)	0.248 ± 0.028	2
(V-Ks)	4.57	1,2
(J-Ks)	0.843 ± 0.029	2
μ_v	210 ± 4 mas yr^{-1}	3
μ_τ	5 ± 4 mas yr^{-1}	3
v_{pec}	0.4 ± 0.3 km s^{-1}	3
Kinematic Distance	16.6 ± 0.3 pc	3
Predicted RV	-33.0 ± 0.1 km s^{-1}	3
Predicted M_{Ks}	10.01 ± 0.05	3
Predicted M_V	14.6	3
Photometric Distance	∼80 pc	3

References: (1) Lepine & Shara (2005), (2) Cutri et al. (2003), (3) this work. Kinematic distance and predicted values assume that the star shares the 3D velocity of 51 Peg.

is -34.9 km s^{-1}. Given the predicted kinematic distance and perpendicular proper motion, the peculiar velocity is 0.9 ± 0.2 km s^{-1} (which corresponds to the *minimum* velocity difference between NLTT 54064 and 51 Peg).

At the kinematic distance 11.6 pc, NLTT 54064 would have an absolute magnitude of M_{Ks} = 8.36 ± 0.05, some 2.0 magnitudes below the main sequence, and 2.5 mag below the [Fe/H] = 0.2 V-K_s vs. M_{Ks} sequence of Johnson & Apps (2009) (Figure 1). If NLTT 54064 is a field M dwarf unassociated with 51 Peg, I estimate a photometric distance of ∼34 pc for NLTT 54064, nearly identical to that estimated by Lepine & Shara (2005) (32.5 pc). At this distance the star would have a tangential velocity of ∼35 km s^{-1}. Similar to the first star, I find that while NLTT 54064 shows *projected* motion similar to 51 Peg (within ∼1 km s^{-1} peculiar velocity), its color-magnitude position at the predicted kinematic distance (∼12 pc) is completely inconsistent with being a [Fe/H] = 0.2 M-dwarf.

2.3.1 NLTT 54007

NLTT 54007 (= LP 520-24 = 2MASS J22300000+1523483) is situated 8°.45 from 51 Peg. Its position, proper motion, and relevant photometry is listed in Table 4. Luyten (1979) considered the star 'k' type based on photographic colors, however no spectroscopic type for the star has been reported in the literature. V magnitudes of 14.884 (Rapaport et al. 2001), 14.926 ± 0.184 (Ducourant et al. 2006), 14.67 ± 0.40 (Lasker et al. 2008), 15.04 (Salim et al. 2003) have been reported. I adopt a median V magnitude of 14.91. The V-K_s and H-Ks colors in Table 4 are both consistent with an

Table 3 Properties of NLTT 54064

Property	Value	Ref.
α(ICRS, J2000)	337°.813782	1
δ(ICRS, J2000)	+17°.16238	1
μ_α	206.0 ± 4.2 mas yr^{-1}	2
μ_δ	67.1 ± 4.2 mas yr^{-1}	2
V mag	13.12	1
J mag	9.518 ± 0.022	4
H mag	8.903 ± 0.021	4
Ks mag	8.671 ± 0.018	4
(J-H)	0.615 ± 0.031	4
(H-Ks)	0.232 ± 0.028	4
(V-Ks)	4.45	3
(J-Ks)	0.847 ± 0.029	3
μ_υ	216.0 ± 4.2 mas yr^{-1}	3
μ_τ	16.2 ± 4.2 mas yr^{-1}	3
v_{pec}	0.9 ± 0.2 km s^{-1}	3
Kinematic Distance	11.6 ± 0.2 pc	3
Predicted RV	-34.9 km s^{-1}	3
Predicted M_{Ks}	8.36 ± 0.05 mag	3
Predicted M_V	12.81	3
Photometric Distance	$\sim$34 pc	3

References: (1) Lepine & Shara (2005), (2) Zacharias et al. (2004), (3) calculated by author from available data, (4) Cutri et al. (2003). Kinematic distance and predicted values assume that the star shares the 3D velocity of 51 Peg.

Table 4 Properties of NLTT 54007

Property	Value	Ref.
α(ICRS, J1991.25)	337°.5001106	1
δ(ICRS, J1991.25)	+15°.3967478	1
μ_α	201.8 ± 4.2 mas yr^{-1}	1
μ_δ	64.4 ± 4.2 mas yr^{-1}	1
V mag	14.91	2
J mag	11.522 ± 0.022	3
H mag	10.931 ± 0.022	3
K_s mag	10.690 ± 0.020	3
(J-H)	0.591 ± 0.031	3
(H-Ks)	0.241 ± 0.030	2
(V-Ks)	4.22	2,3
(J-Ks)	0.832 ± 0.030	3
μ_υ	209.3 ± 4.2 mas yr^{-1}	2
μ_τ	32.7 ± 4.2 mas yr^{-1}	2
v_{pec}	1.8 ± 0.2 km s^{-1}	2
Kinematic Distance	11.5 ± 0.2 pc	2
Predicted RV	-35.0 ± 0.1 km s^{-1}	2
Predicted M_{Ks}	10.38 ± 0.05	2
Predicted M_V	14.60	2
Photometric Distance	$\sim$87 pc	2

References: (1) Zacharias et al. (2004), (2) calculated by author from available data, (3) Cutri et al. (2003). Kinematic distance and predicted values assume that the star shares the 3D velocity of 51 Peg.

M2 dwarf. I adopt the proper motion for NLTT 54007 from Zacharias et al. (2004), which is similar to other motions with larger uncertainties quoted by Lepine & Shara (2005), Roeser et al. (2008), & Salim et al. (2003).

The proper motion of NLTT 54007 towards the vertex of 51 Peg is μ_υ = 209.3 $\pm$ 4.2 mas yr^{-1}, and the perpendicular component is μ_τ = 32.7 $\pm$ 4.2 mas yr^{-1}. If NLTT 54007 shares the space velocity of 51 Peg, its proper motion is consistent with a kinematic distance of 11.5 $\pm$ 0.2 pc (parallax 86.6 $\pm$ 1.9 mas), and one would predict a radial velocity of -35.0 km s^{-1}. At the kinematic distance, the perpendicular motion μ_τ is consistent with a peculiar velocity of 1.8 ± 0.2 km s^{-1}.

At the kinematic distance of 11.5 pc, NLTT 54007 would have an absolute magnitude of M_{Ks} = 10.38 ± 0.05. For its V-K_s color, this is 4.4 magnitudes below the main sequence, and 4.81 mag below the [Fe/H] = 0.2 V-K_s vs. M_{Ks} sequence of Johnson & Apps (2009) (see Figure 1). If NLTT 54064 were a typical field M dwarf, its colors suggest a photometric distance of $\sim$87 pc for NLTT 54064, and a probable tangential velocity of $\sim$87 km s^{-1} at this distance. As with the other two stars, the kinematic and color-magnitude data for NLTT 54007 are not consistent with it being physically related to 51 Peg.

3 Discussion

There is one last possibility to consider for salvaging the hypothesis that these stars could be co-moving with 51 Peg: the possibility that these stars are white dwarfs. However none of the synthetic atmosphere models for degenerate stars by Bergeron et al. (1995) produce objects as red as these three stars (V-K_s $\simeq$ 4.2-4.6), and indeed the observed V-K_s colors of both DA and non-DA white dwarfs are generally less than V-K_s $<$ 2.2 (Bergeron et al. 1997). Hence there is no reason to believe a priori that the three stars could be cool white dwarf companions to 51 Peg either.

I have demonstrated that while the proper motions of the three M dwarfs are similar to that of 51 Peg, their inferred kinematic and photometric distance estimates are very discordant, and hence none of the stars are likely to be co-moving stellar 'siblings' with 51 Peg. Despite the lack of trigonometric parallax measurements for these faint Luyten proper motion stars (NLTT 55547, 54064, and 54007), it appears that the available color-magnitude and astrometric data are probably sufficient to convincingly rule out Greave's (2006) claim of physical association between these stars and 51 Peg. I estimate photometric distances of $\sim$80, $\sim$34, and $\sim$87 pc for NLTT 55547, 54064, and 54007, respectively. The exercise demonstrates the dangers of relying too heavily on proper motions alone on interpreting the nature of widely separated stars of similar projected motion.

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